

Viability of 3 D Woven Carbon Cloth and Advanced Carbon-Carbon Ribs for Adaptive Deployable Entry Placement Technology (ADEPT) for Future NASA Missions*

**E. Venkatapathy¹, K. H. Peterson², M.L. Blosser³
and J. O. Arnold¹**

¹NASA Ames Research Center

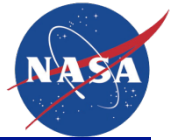
²ERC, Inc. at NASA Ames

³NASA Langley Research Center

***National Space and Missiles Materials Symposium
June 24-28, Bellevue Washington***

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Outline



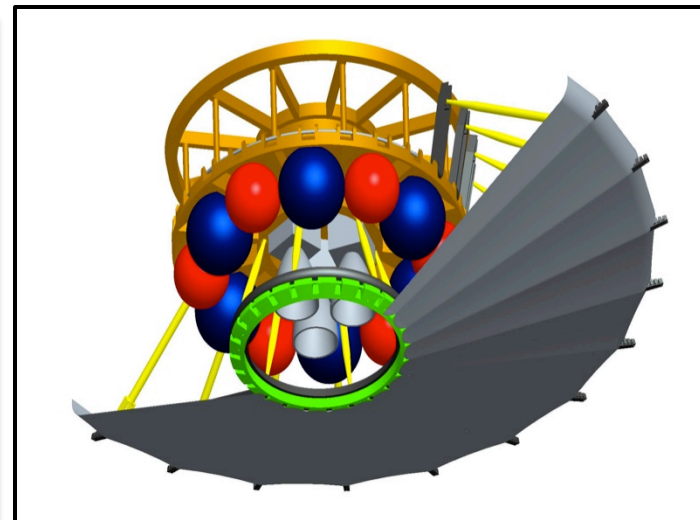
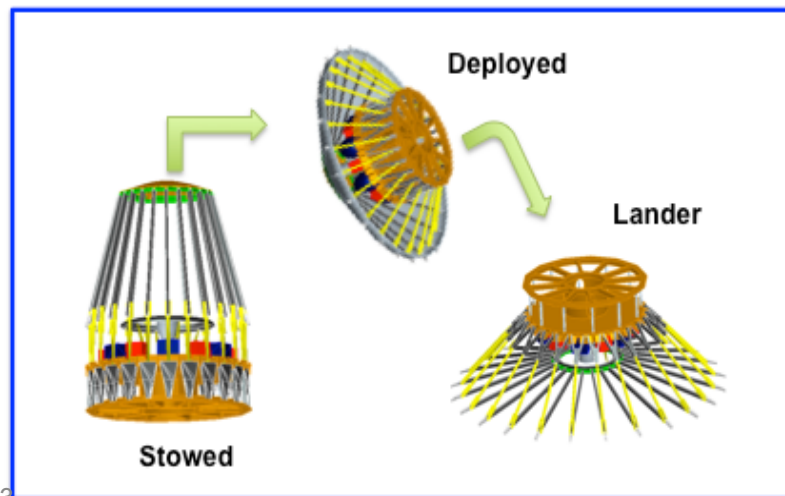
- **Background**
 - Adaptive Deployable Entry Placement Technology (ADEPT) Concept
- **Near-term Application of ADEPT for Venus Robotic Mission**
 - Venus Intrepid Tessera Lander (ADEPT-VITaL) Mission.
- **Arcjet testing**
 - Objectives
 - ADEPT-VITaL entry environments
 - Test articles and Instrumentation
 - Results
 - Fully Implicit Ablation and Thermal (FIAT) and its use as a
 - Preliminary Thermal Response Model for carbon fabric
- **Thermal structural analysis and early testing**
- **Summary and forward work**

Adaptable, Deployable, Entry and Placement Technology (ADEPT) Concept for Human Mars Exploration

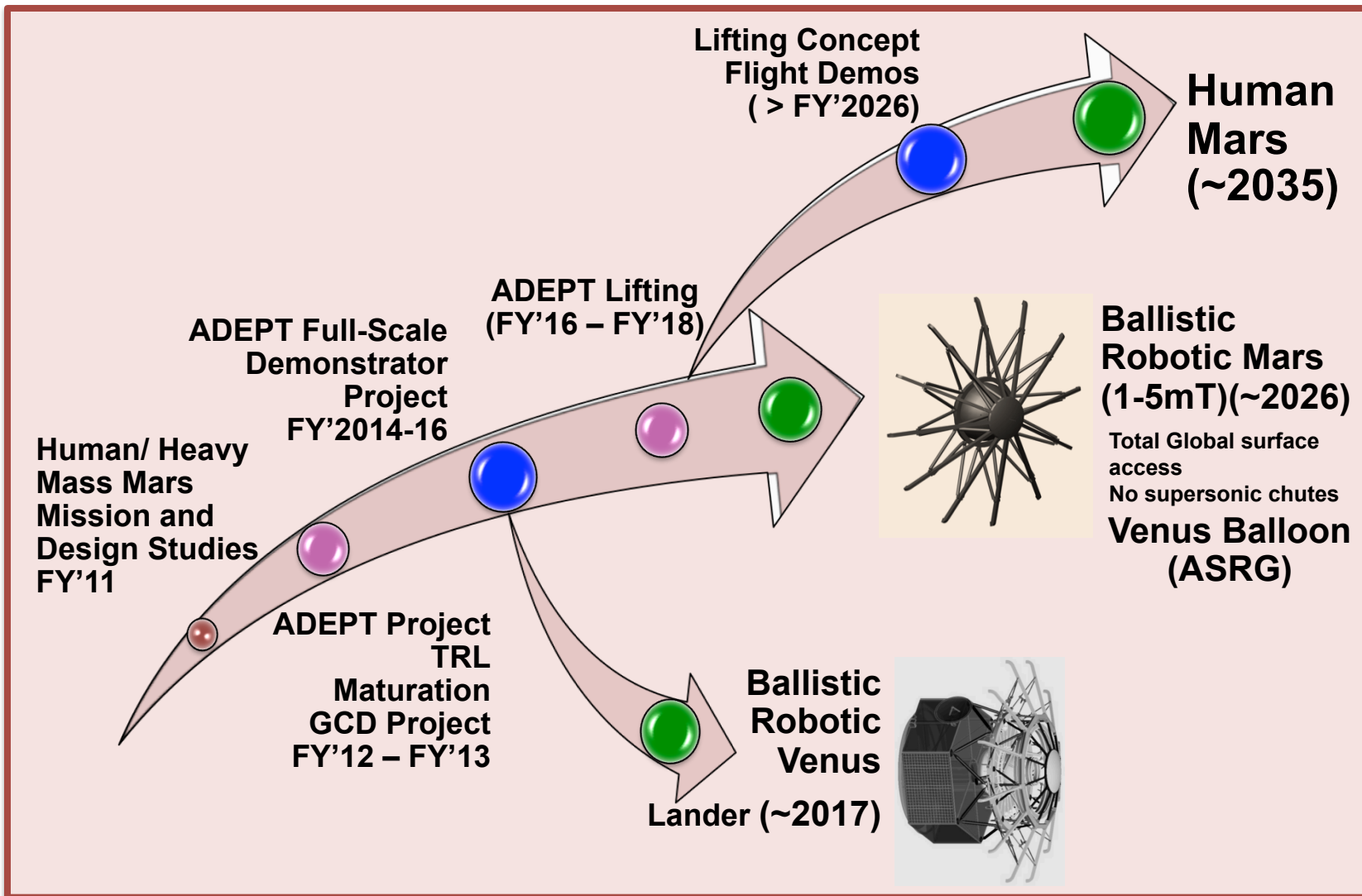


ADEPT can be scaled to deliver 40 MT payloads to the surface of Mars

- A rigid structural ring that reacts to the primary aerodynamic load and provides a simple interface to the delivered payload;
- A self-contained winch deployment system;
- Deployable “rigid” spokes for transmitting loads to the primary ring;
- Flexible thermal protection system (TPS) material;
- An ejectable nose heat shield for exposing the retro-propulsion system; and
- A primary gimbaled design for pivoting of the aeroshell and thereby enabling GN&C.
- A design that transforms the aeroshell into a lander configuration



ADEPT Technology Maturation and Mission Infusion Timeline

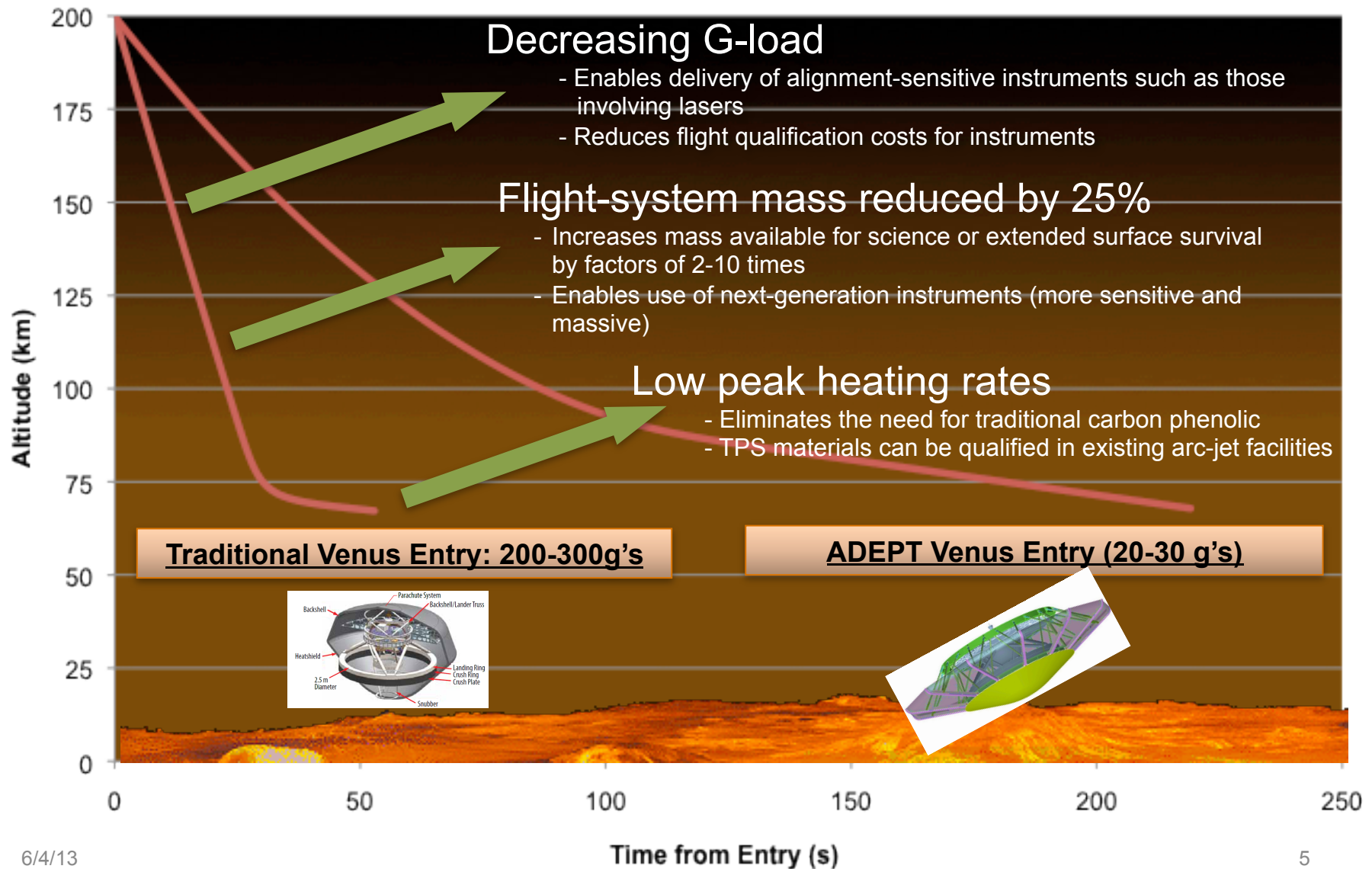


ADEPT is an Entry Architecture that delivers for Game Changing Science and Exploration Missions in the Near, Mid, and Long term!

Status Quo – The State of the Art Venus Entry



ADEPT

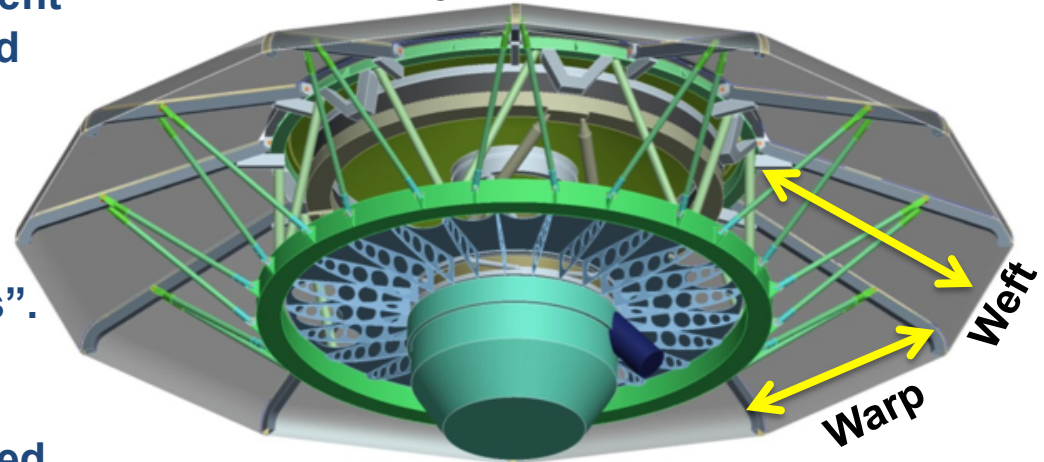


ADEPT-VITaL

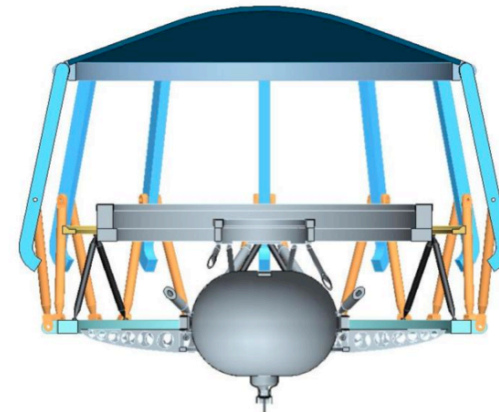


- Adaptive Deployable Entry Placement Technology (ADEPT)-Venus Intrepid Tessera Lander¹.
- Blunt entry system with dry woven carbon, 0.15 inch thick “skin” and Advanced Carbon-Carbon “ribs”.
- Low ballistic number and shallow entry flight angle gives ~10 X reduced deceleration and entry heating, enabling better science.
- Carbon fabric is taut, and must sustain combined entry heating and bi-axial mechanical loading.
- *Warp direction perpendicular to flow and weft direction is parallel to flow*

Deployed in Space



Stowed for Launch



¹Smith, B. Venkatapathy, E., Yount, B. Gage, P. Glaze, L. and Baker, C. *Venus in-Situ Explorer Mission Design Using a Mechanically Deployed Aerodynamic Decelerator* Big Sky IEEE Montana, March 2-9, 2013.

Bi-axial Loaded Aerothermodynamic Mechanical (BLAM) Test Objectives



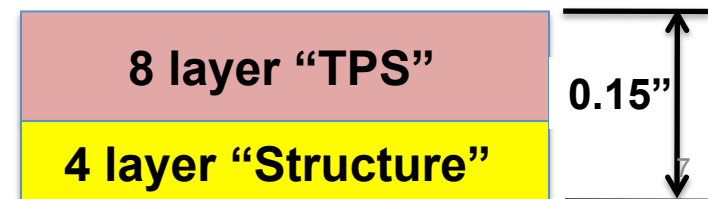
1. Evaluate the capability of the weave to maintain structural integrity under combined, flight-like aerothermodynamic heating and bi-axial tensile loads.
2. Evaluate the rate of layer loss as a function of different aerothermal and biaxial loadings.

Secondary: Provide arcjet tested fabrics to:

- Evaluate the residual load-bearing capacity of post-heated samples
- Examine the microstructure of arcjet tested fabric

3 D Dry Woven Carbon Fabric that is specially designed to withstand the combined thermal and mechanical loads

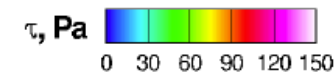
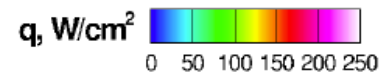
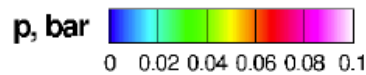
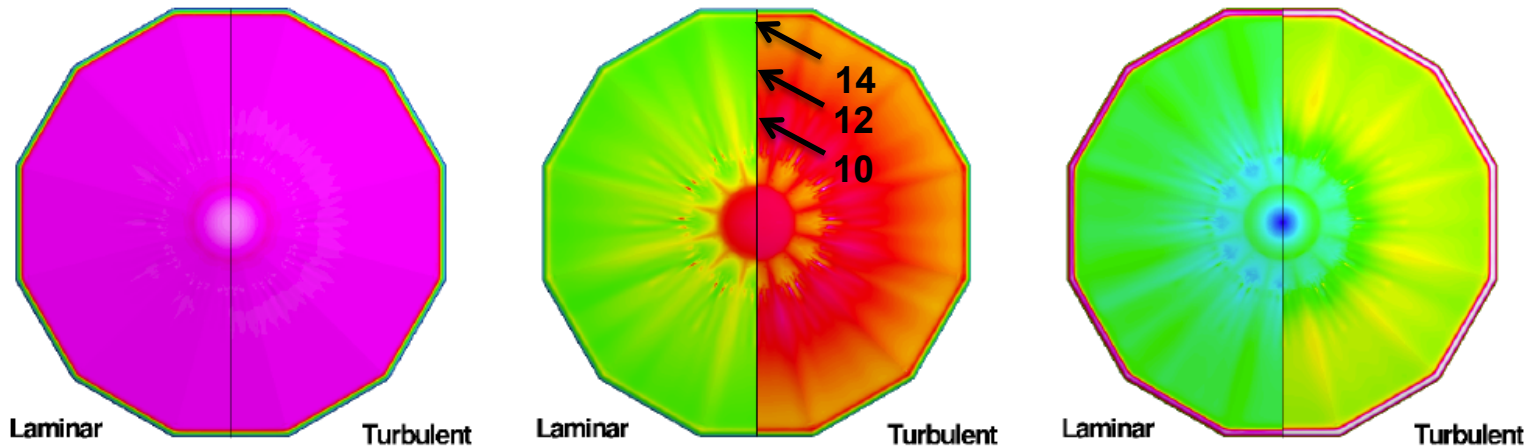
²Arnold, J. O. et. al, "Arcjet testing of Woven Carbon Cloth for Use on ADEPT", IPPW-10 San Jose State Univ. June 17-21, 2013. Manufactured by Bally Ribbon Mills.



ADEPT-VITaL Aerothermodynamic Hot Wall Environment

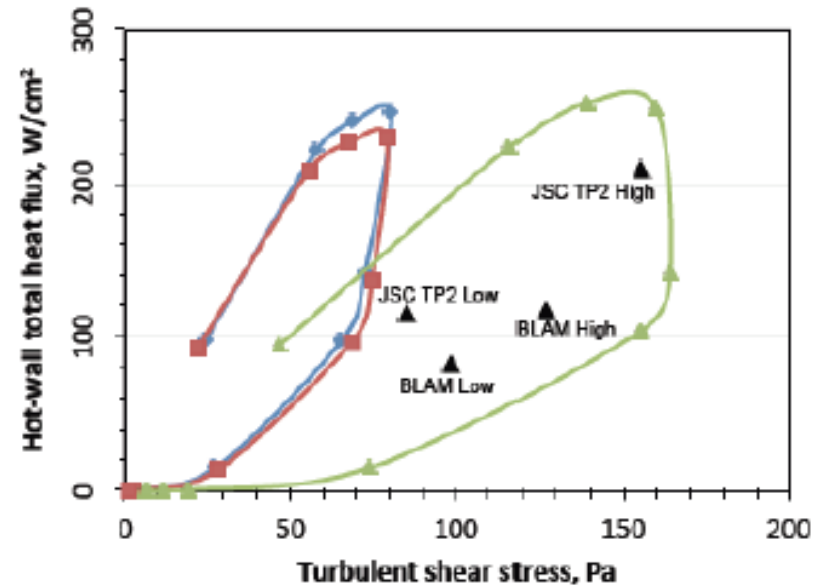
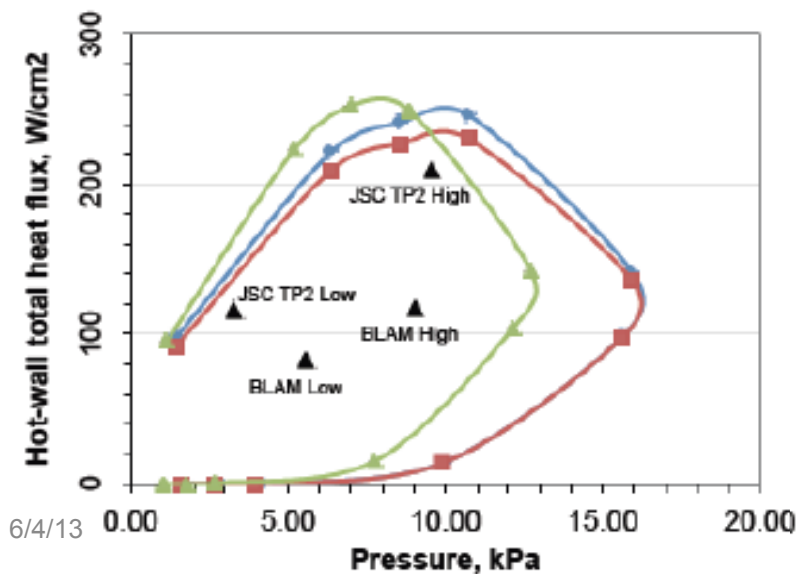
(Head on Plots for Convective Component at Peak Heating – D.K Prabhu)

Total heating , Accounting for Radiation ~ 32 Percent Higher)



BP #10 BP #12 BP #14

BP #10 BP #12 BP #14



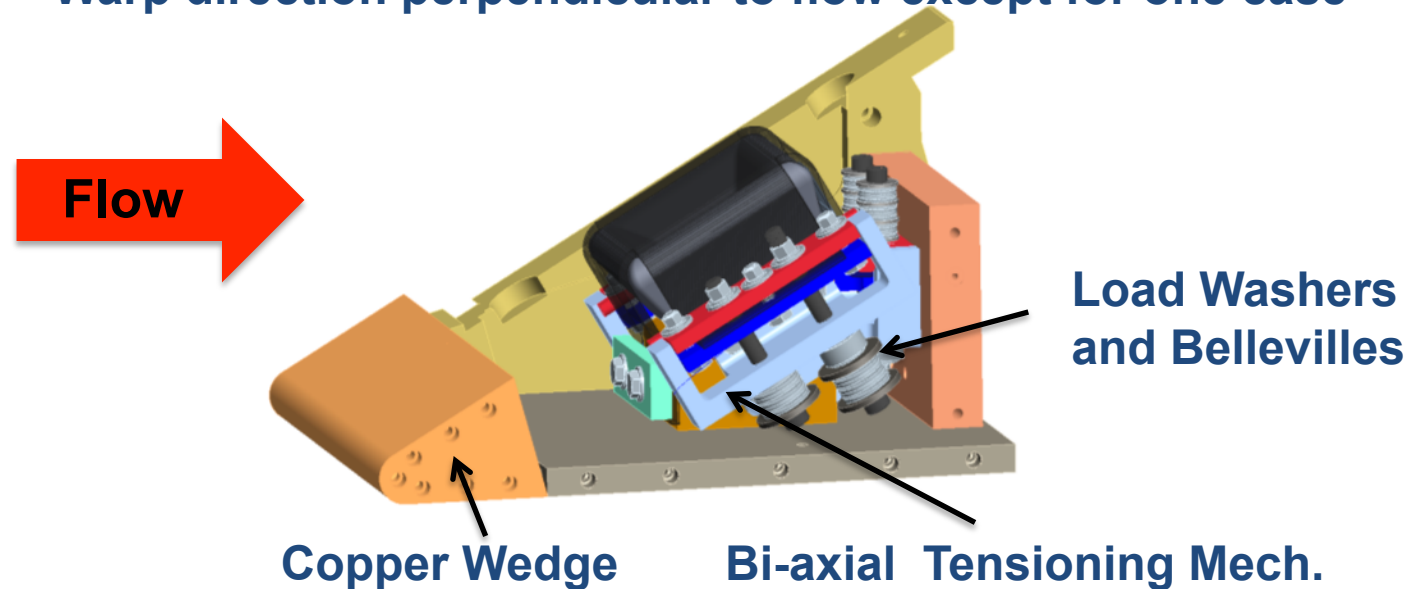
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ArcjetTest Article* and Instrumentation



*Graphite top plate not shown

- Design ensured load carried in structural layers
- Warp direction perpendicular to flow except for one case

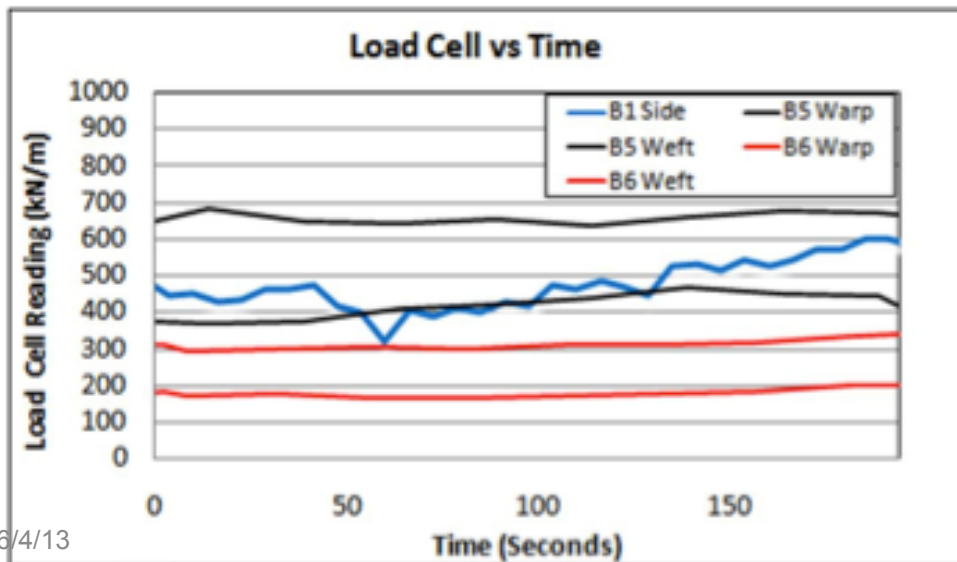


- Internal thermocouples to ensure load washer temps not effecting calibration.
- High definition video to observe layer loss.
- Pyrometers to measure surface temperature

Structural Integrity During Combined Environment Testing



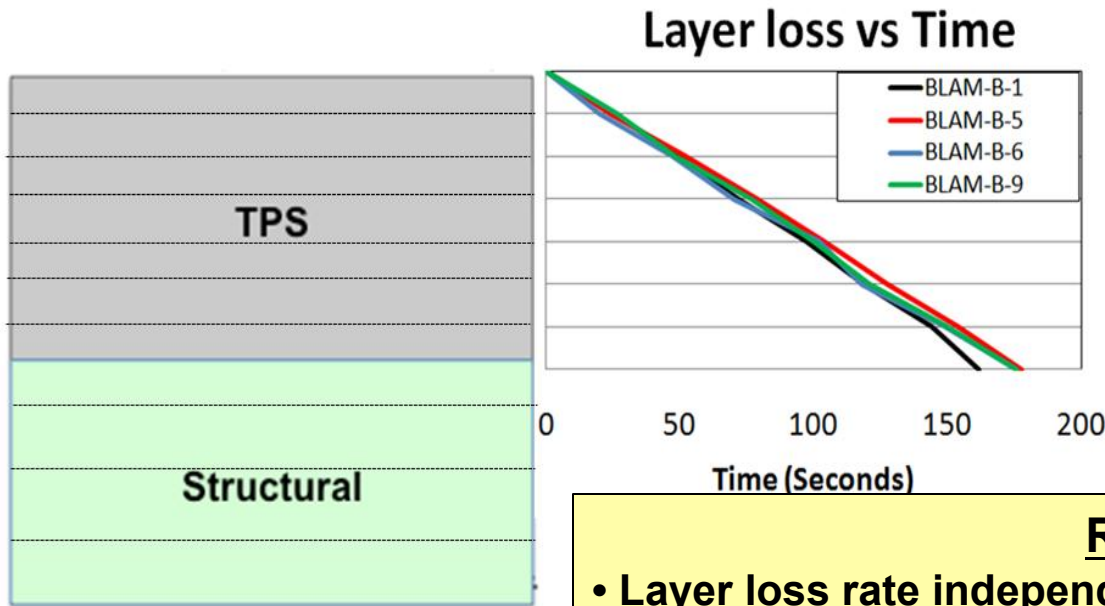
Run	Model	C-W Heat Flux (W/cm ²)	Warp Running Load (N/m)	Weft Running Load (N/m)	Insertion Time (s)	8-Layer Removal (s)
1	B-1	97	65673	0	175	162
2	B-2	136	131345	65673	119	114
3	B-3	136	131345	65673	35	N/A
4	B-4	97	65673	32924	135	N/A
5	B-5	97	131345	65673	185	178
6	B-7	97	131345	65673	139	N/A
7	B-6	97	65673	32924	205	176
8	B-8	97	65673	32924	90	N/A
9	B-9	97	65673	131345	195	177



Results

- Minimal change in load demos tensile integrity of fabric
- Test heat loads >> VITaL mission

Layer Loss at 97 W/cm² (C-W)



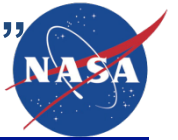
Results

- Layer loss rate independent of bi-axial load levels B-5 & B-6 (full and ½ flight).
- Layer loss independent of warp/weft load flip B-5 and B-9.
- Test with uni-axial loading (B-1) sees slightly higher rate of layer loss.
- Post arcjet tested fabric tensile strength 3 X that req'd for VITaL mission³.
- Exposed top of structural layer thinned by oxidation, but not on the bottom most layer³.

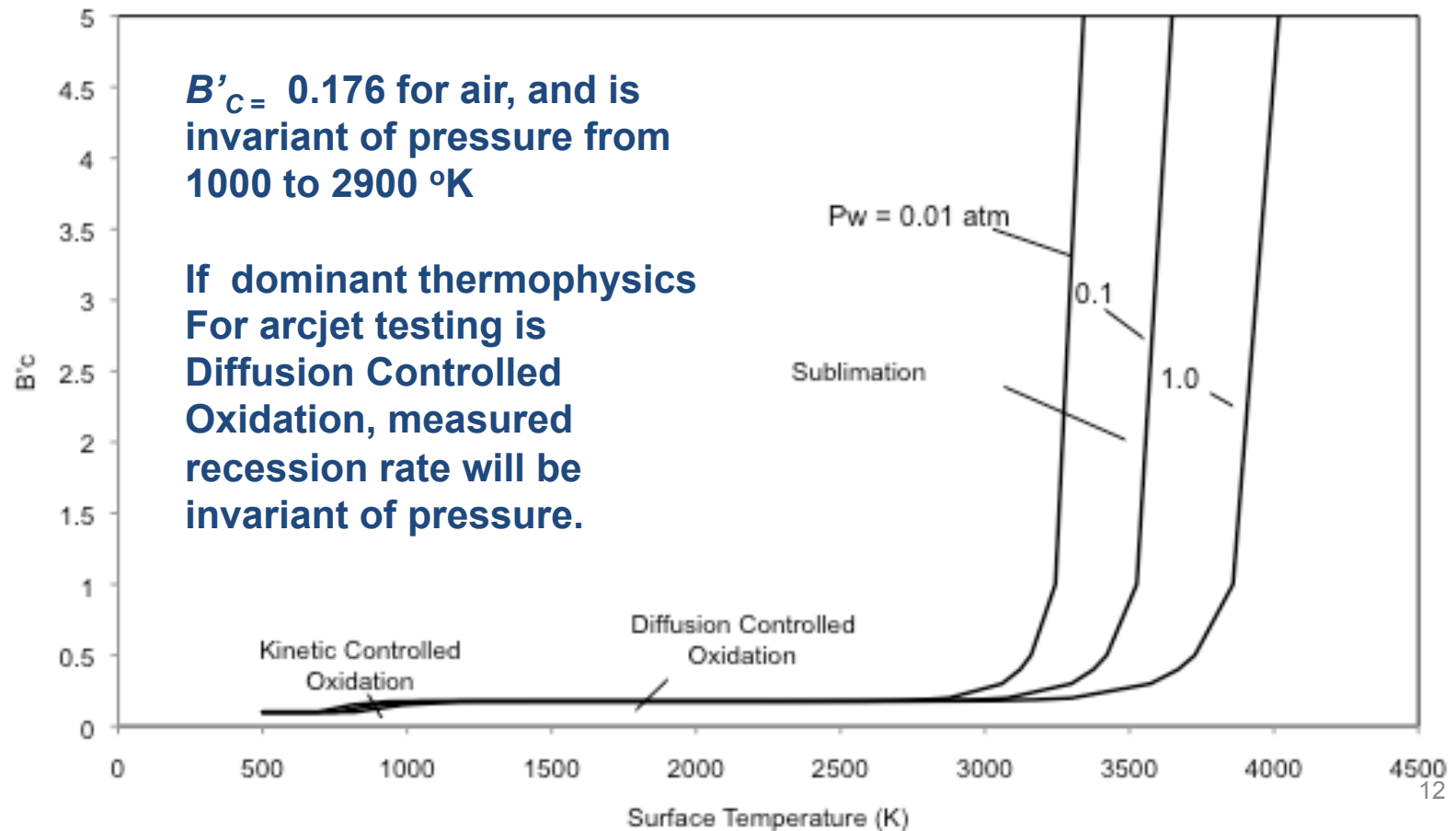
³Agrawal, P., et. al.,
 “Micromechanical
 Characterization and
 Testing of Carbon Based
 Woven TPS Materials”,
 Cocoa Beach Conference.
 Cocoa Beach FL, January
 2013.

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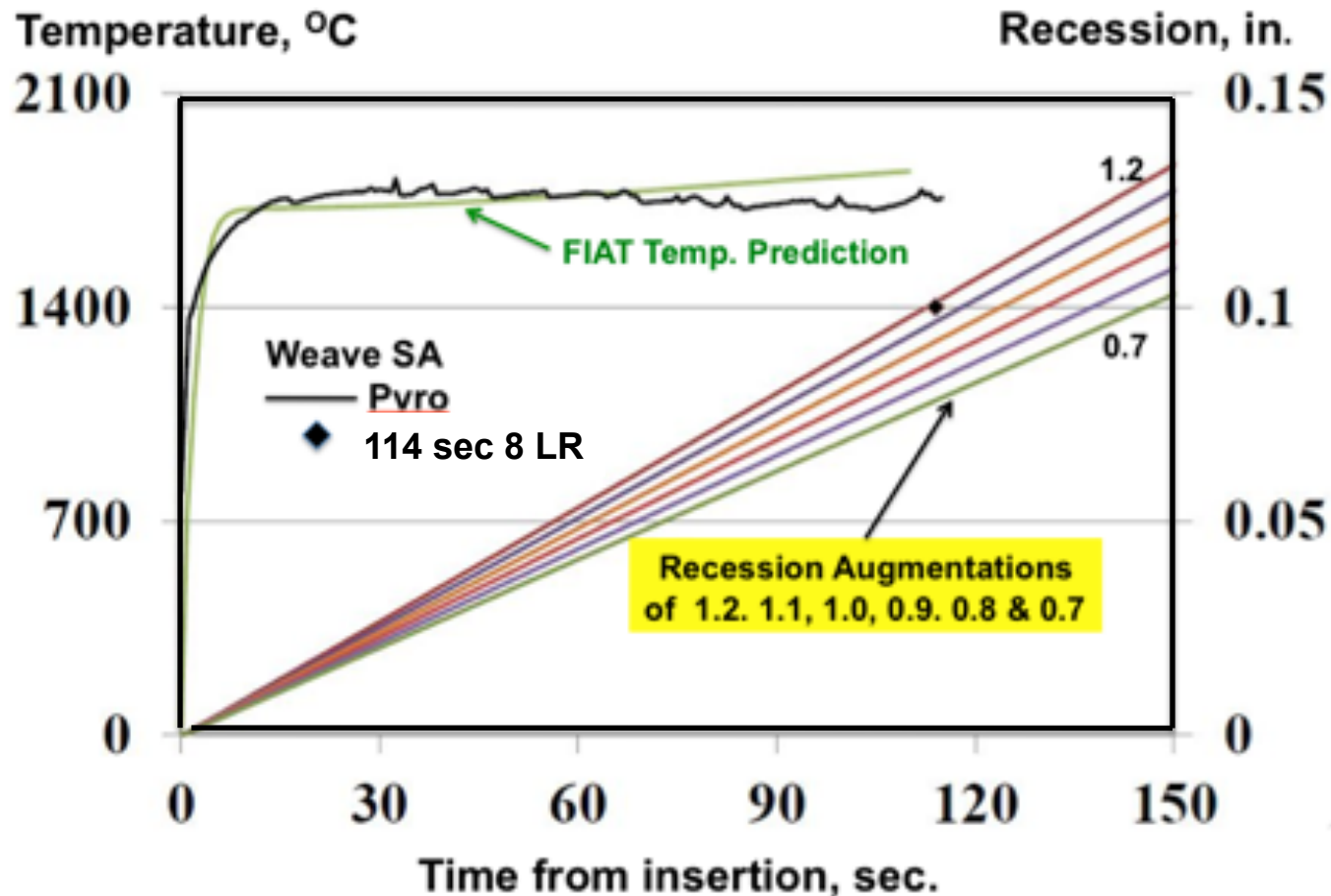
FIAT Predictions for Carbon Fabric Layer Removal “Recession”



- Solid carbon recession rate = $S_{\dot{o}} = B'_c \times C_H / \rho$ Layer removal = $(1 + RA) \times B'_c \times C_H / \rho$
- RA = Recession Augmentation, B'_c (below), $C_H = \dot{q} / (H_e - H_w)$ and ρ = fabric density
- FIAT predictions for $S_{\dot{o}}$ on an equivalent solid carbon slab with $RA = 0.0$, are about half those measured for layer removal on fabrics in arcjet testing.



FIAT Predictions (Y-K Chen) and BLAM Measurements 136 W/cm² (C-W) and 9.1 kPa



- Recession Augmentation (RA) of ~ 1.2 for FIAT prediction of recession on hypothetical equivalent carbon layer required to match measured layer loss.
- Excellent comparison of predicted and measured surface temperature.

Summary of FIAT vs Test Data



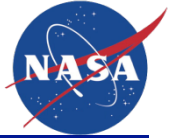
Facility	Model	Total Layers	Thick-ness “	Qdot W/cm ²	Press, kPa	Layers removed	Remove Time, s	RA
ARC/IHF	B-1 (SA)	12	0.15	97	5.63	8	162	1.2
ARC/IHF	B-5 (SA)	12	0.15	97	5.63	8	178	0.9
ARC/IHF	B-6 (SA)	12	0.15	97	5.63	8	176	0.9
ARC/IHF	B-9 (SA)	12	0.15	97	5.63	8	177	0.9
ARC/IHF	B-2 (SA)	12	0.15	136	9.1	8	114	1.2
JSC/TP2	Weave SA	8	0.10	136	3.35	4	78	0.9
JSC/TP2	Weave D	8	0.10	136	3.35	4	75	1.0
JSC/TP2	Weave SA	8	0.10	246	9.6	4	44.4	0.7

IHF: Interaction Heating. TP2: Test Point 2. Weave D: Predecessor and similar to Weave SA

- FIAT with RA of 0.9 ± 0.2 ~ Correlates layer removal across different facilities, test articles, fabric thickness, layers removed, and different heat fluxes and pressures.
- Conclusions:
 - Fabric layer removal ~ 2 X the rate for an equivalent carbon film, most likely owing to the fabric's greater surface area presented to the arcjet flow.
 - Correlation at 136 W/cm² and ~ 3 X pressure difference suggests that diffusion controlled oxidation is the dominant thermo physics for this range of conditions.

JSC Data from Arnold, J. O. et. al, “Arcjet testing of Woven Carbon Cloth for Use on ADEPT”, IPPW-10 San Jose State Univ. June 17-21, 2013.

Conclusions Based on Arcjet Testing and Analysis

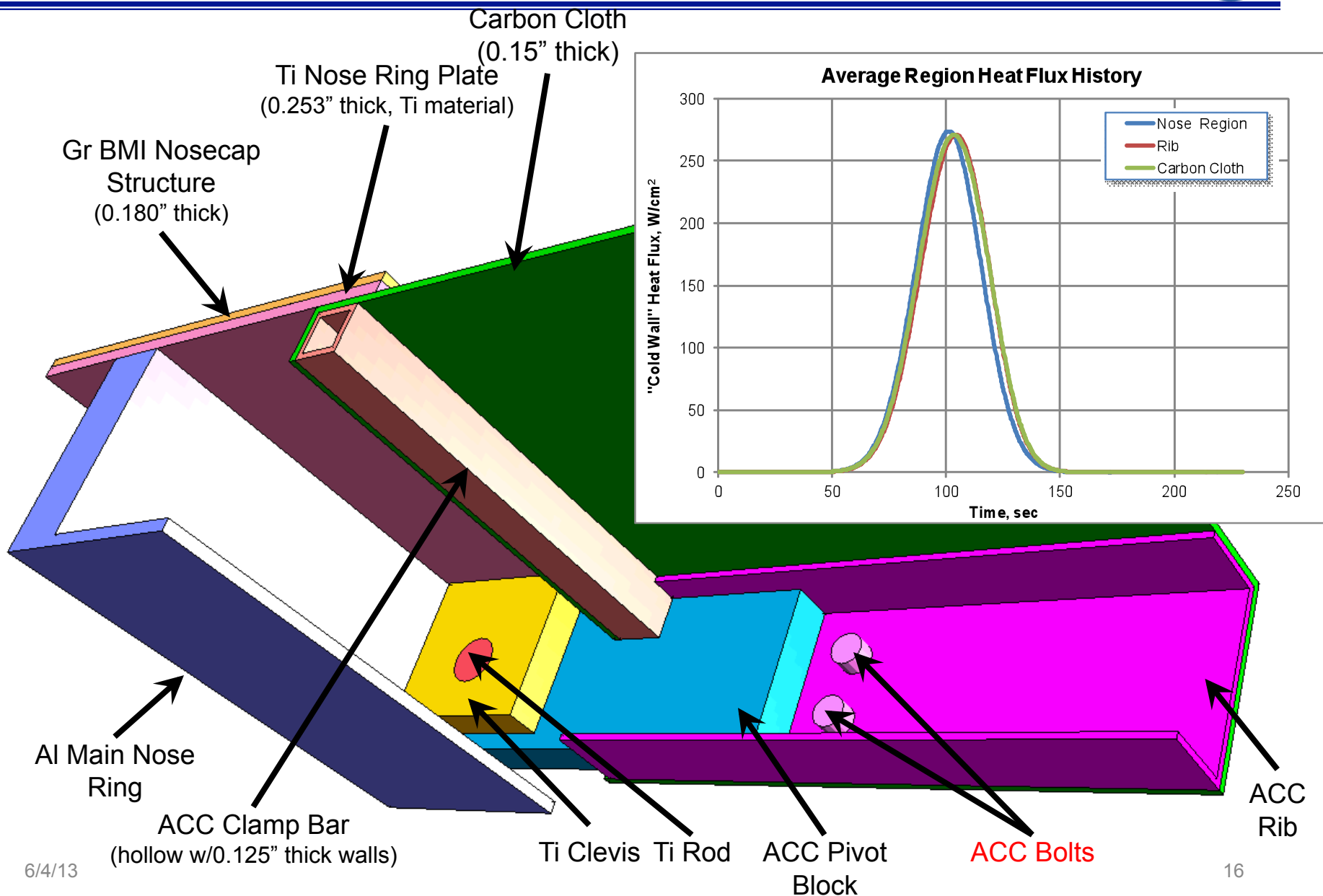


- ADEPT's 3 D weave SA carbon fabric “skin” is viable to function as the TPS and as the structural member that transfers deceleration loads to its “skeleton”.
- We have a preliminary FIAT-based Thermal Response Model for carbon fabric:
 - Recession rate = $S_{\text{dot}} = (1 + RA) \times B'_c \times C_H/\rho$ where $RA = 0.9 \pm 0.2$ nearly correlates all arcjet data obtained to date.
 - $(1 + RA)$ is approximately 2, and is independent of test conditions probably due to the fabric presenting a larger surface area to the flow compared to that from a solid layer.
 - FIAT does a good job of predicting fabric temperatures. Very important to serve as boundary condition for thermal structural analysis of ADEPT structure
 - Arcjet data at 136 W/cm² at 3.35 and 9.1 kPa suggests that diffusion controlled oxidation dominates the testing thermophysics
- FIAT thermal response model can be modified to account for performance in CO₂ rich atmospheres using test data obtained in air to predict flight performance for ADEPT –ViTaL, e.g. Sizing for TPS and its “skin” temperatures.

Simplified Nose –Rib-Fabric 3D Model Geometry – Back Side (T. Squire)



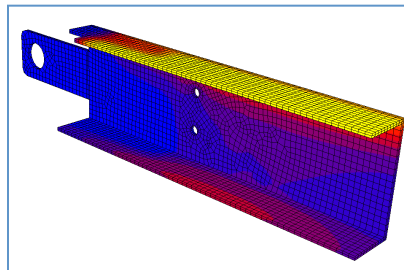
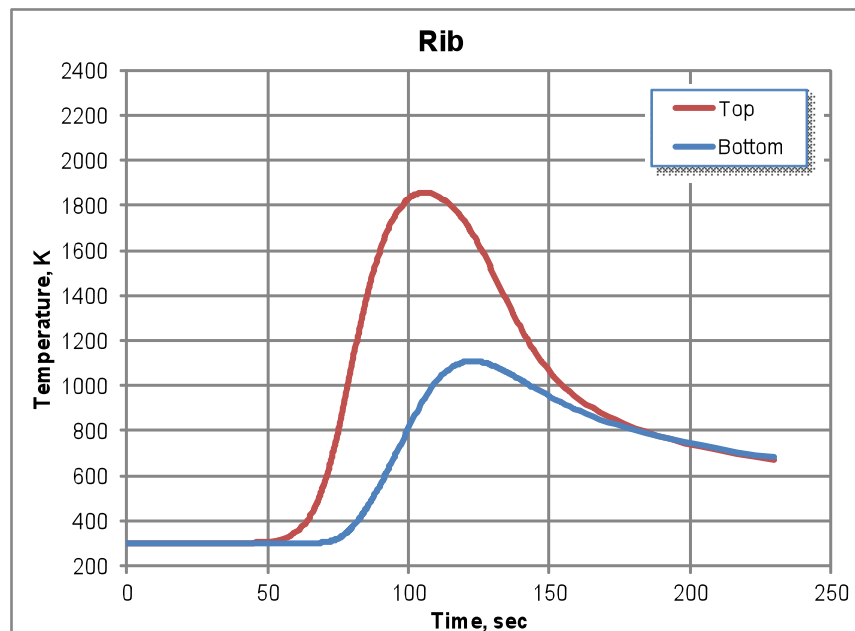
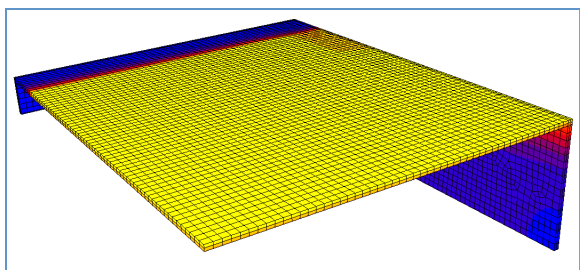
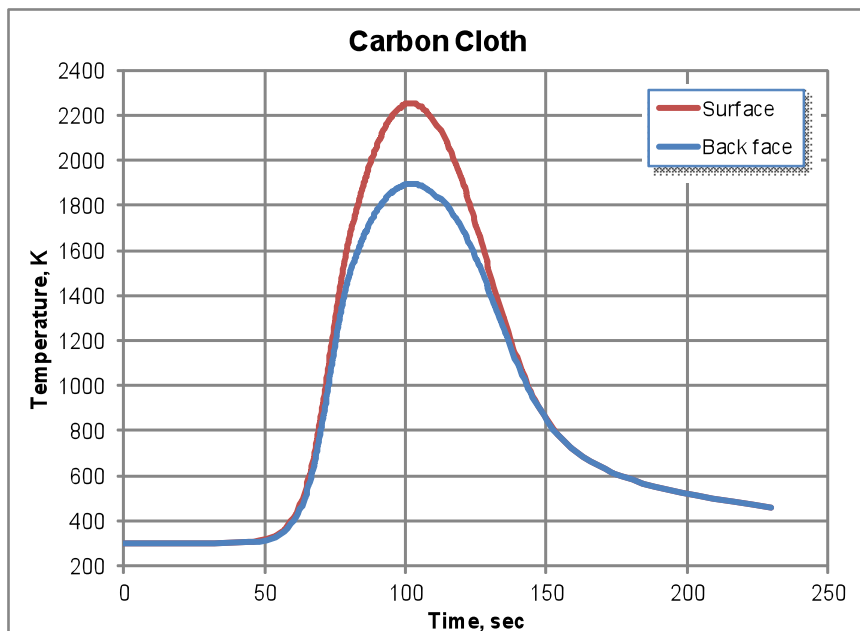
ADEPT



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16

Results – Temperature History (T. Squire)



Preliminary results:

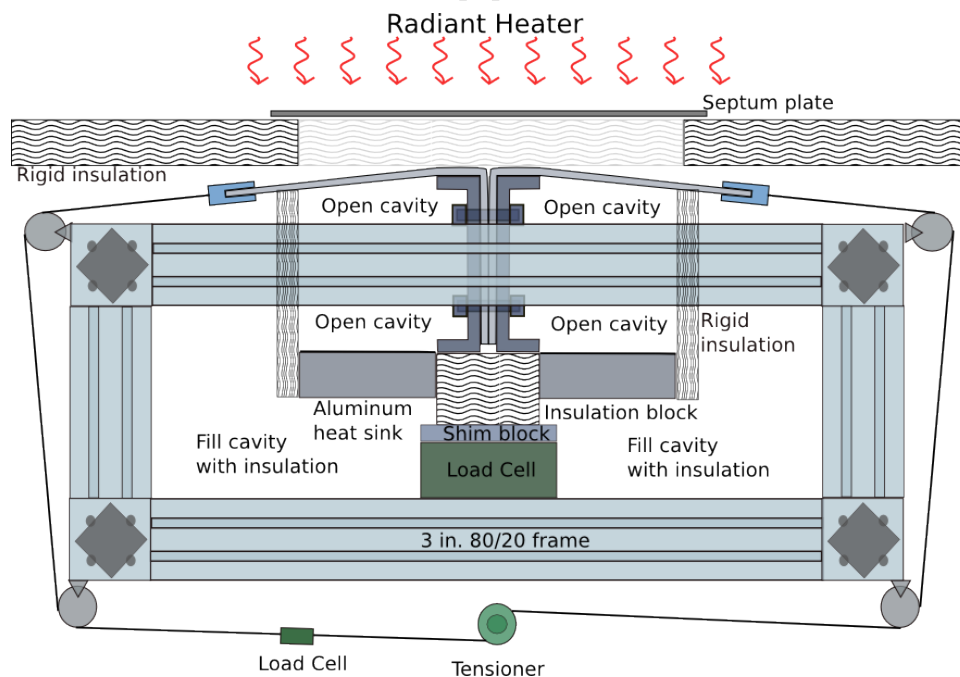
- Carbon cloth, ACC ribs and conventional materials for the nose ring and clevis are viable for ADEPT's thermal structural design
- Cloth-nose TPS design needs work, but solution space exists

Preliminary Thermal/Structural Test



Objective: Measure transient thermal response of rib/cloth joint under combined thermal and mechanical load .and anchor codes

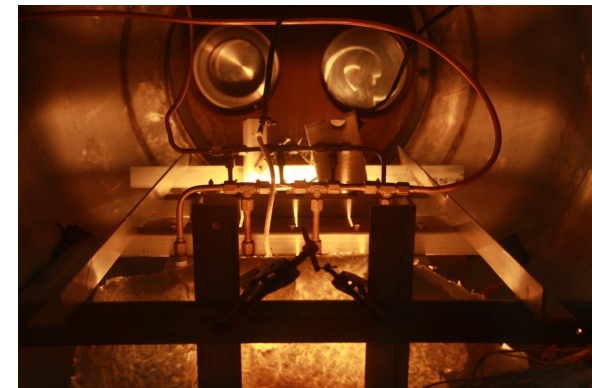
Test Apparatus



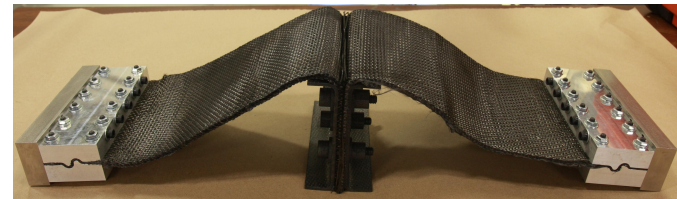
Specimen: 6-inch long rib section and associated cloth

Status

.Heater characterization complete



.Apparatus fabrication and checkout in progress



Summary and Forward Work



- **Arcjet testing and analysis shows that 3 D woven carbon cloth and ACC ribs provide a viable pathway to an ADEPT-VITaL flight vehicle**
- **We have demonstrated a flexible dual use, TPS/Aerodynamic “skin”, that is well suited for ADEPT**
- **A FIAT-based thermal response model has been developed to predict carbon cloth layer removal**
- **Simplified thermal structural testing on rib/cloth interfaces is underway – Goal here is to validate or anchor codes**
- **Future arcjet testing will consider fabric attachments to rib and nose interfaces. Testing at the Sandia solar tower in planning to demonstrate system level tests of cloth/nose/rib/TPS performance**

Acknowledgements



- **The late Bernie Laub for his guidance on the development of FIAT as applied to woven carbon fabric**
- **Dinesh Prabhu and Y-K Chen for DPLR and FIAT calculations supporting the thermal response development**
- **Tom Squire for his thermal-structural analysis**
- **To the BLAM team for the design and building of the arcjet models**
- **To the Ames and JSC arcjet teams for conducting the testing**



BACKUP

Abstract



Viability of 3 D Woven Carbon Cloth and Advanced Carbon-Carbon Ribs for use in Adaptive Deployable Entry Placement Technology for Future NASA Missions

E. Venkatapathy¹, K. H. Peterson², M. L. Blosser² and J. O. Arnold¹

National Space & Missile Materials Symposium June 24 – 28, 2013 Bellevue Washington

This paper describes aerothermodynamic and thermal structural testing that demonstrate the viability of three dimensional woven carbon cloth and advanced carbon-carbon (ACC) ribs for use in the Adaptive Deployable Entry Placement Technology (ADEPT). ADEPT is an umbrella-like entry system that is folded for stowage in the launch vehicle's shroud and deployed prior to reaching the atmospheric interface. A key feature of the ADEPT concept is a lower ballistic coefficient for delivery of a given payload than seen with conventional, rigid body entry systems. The benefits that accrue from the lower ballistic coefficient include factor-of-ten reductions of deceleration forces and entry heating. The former enables consideration of new classes of scientific instruments for solar system exploration while the latter enables the design of a more efficient thermal protection system. The carbon cloth base lined for ADEPT has a dual use in that it serves as the thermal protection system and as the "skin" that transfers aerodynamic deceleration loads to its umbrella-like substructure. Arcjet testing described in this paper was conducted for some of the higher heating conditions for a future Venus mission using the ADEPT concept, thereby showing that the carbon cloth can perform in a relevant entry environment. Recently completed thermal structural testing of the cloth attached to a representative ACC rib design is also described. Finally, this paper describes a preliminary engineering level code, based on the arcjet data, that can be used to estimate cloth thickness for future ADEPT missions and to predict carbon cloth performance in future arcjet tests.

¹ NASA Ames Research Center ² ERC, Inc ³ NASA Langley Research Center

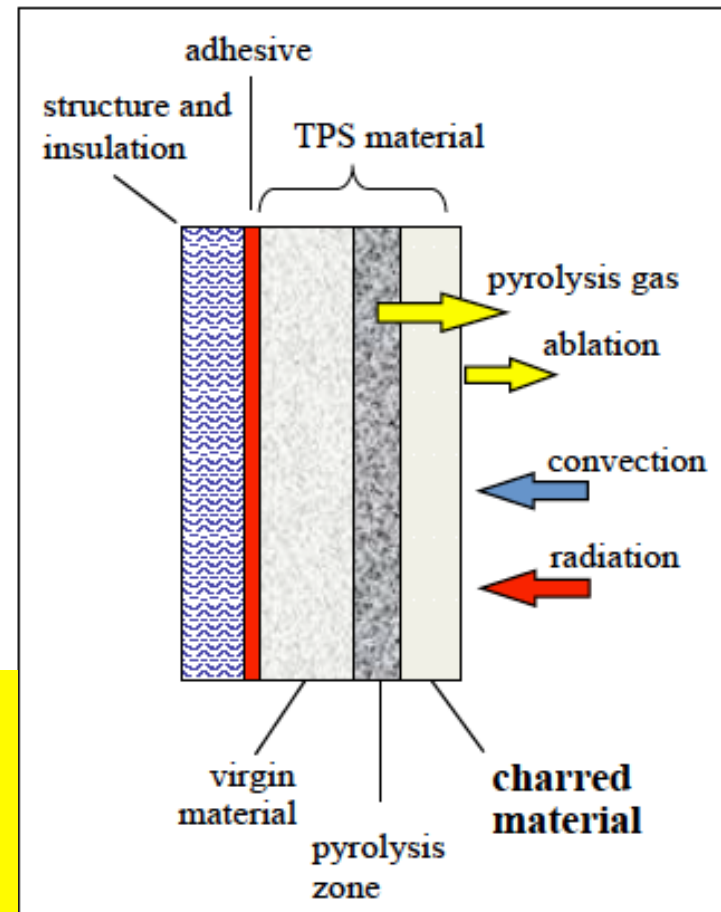
FIAT - Typically used to Size Ablators (PICA, AVCOAT, and SLA)



Fully Implicit Ablation and Thermal-response program*

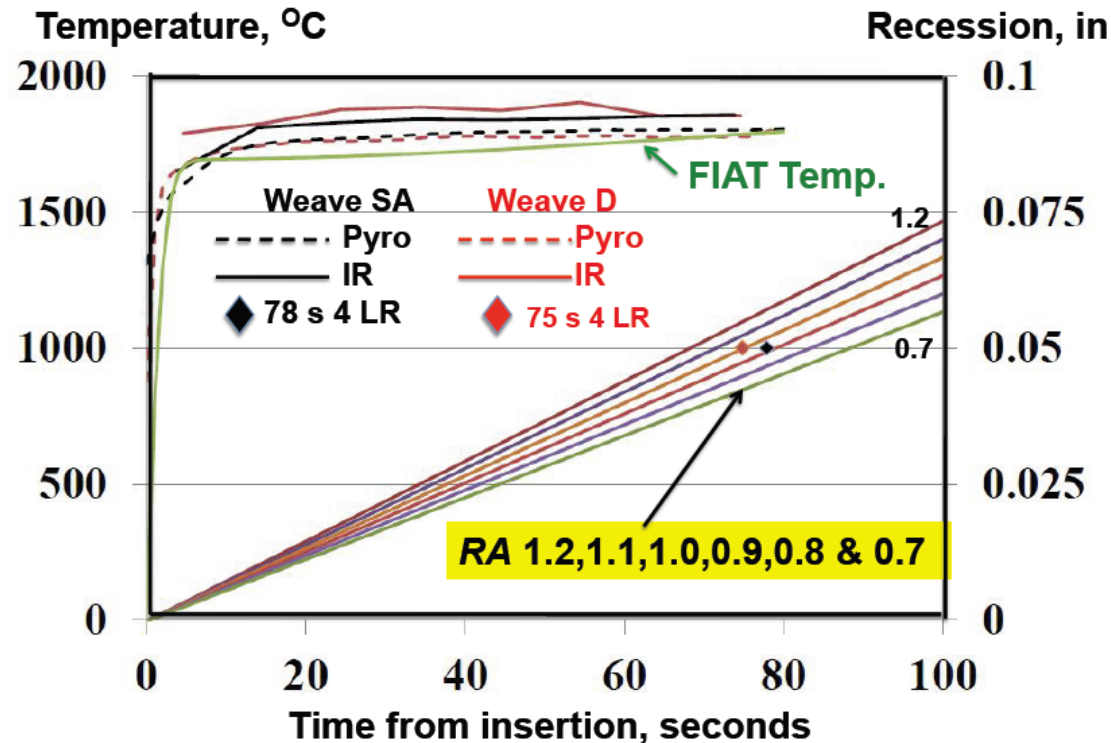
- 1-D time-accurate solution of thermal diffusion with surface ablation and internal pyrolysis
- General multilayer material stack
 - TPS, adhesive, insulation, structure, air gap
 - Planar, cylindrical, or spherical geometry
- Thickness of any layer may be optimized based on temperature limits of underlying materials

B. Laub pioneered the use of FIAT for carbon fabrics by modeling them as a layer of solid carbon of the same thickness and density as the cloth.



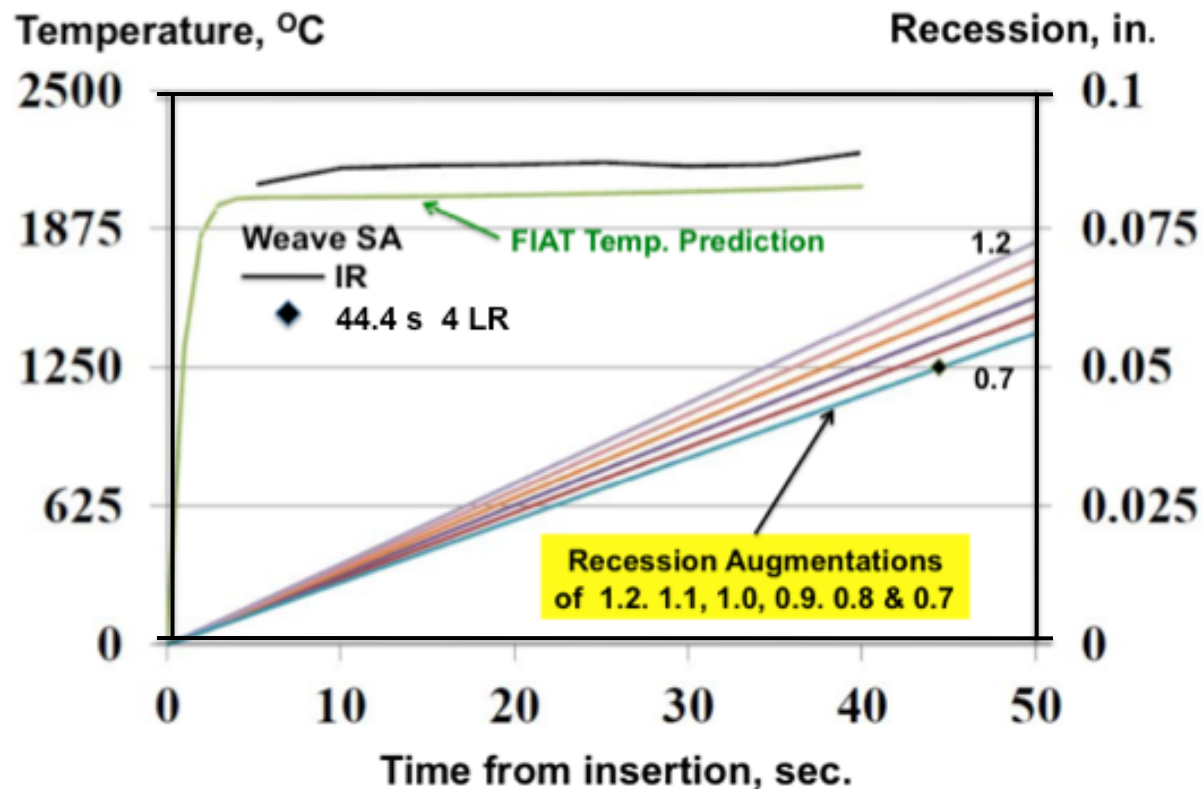
* Y.-K. Chen and F.S. Milos, "Ablation and Thermal Response Program for Spacecraft Heatshield Analysis," *Journal of Spacecraft and Rockets*, Vol. 36, No. 3, 1999, pp. 475-483.

Weaves SA and D at 136 W/cm² and 3.35 kPa and Comparison to the FIAT Prediction



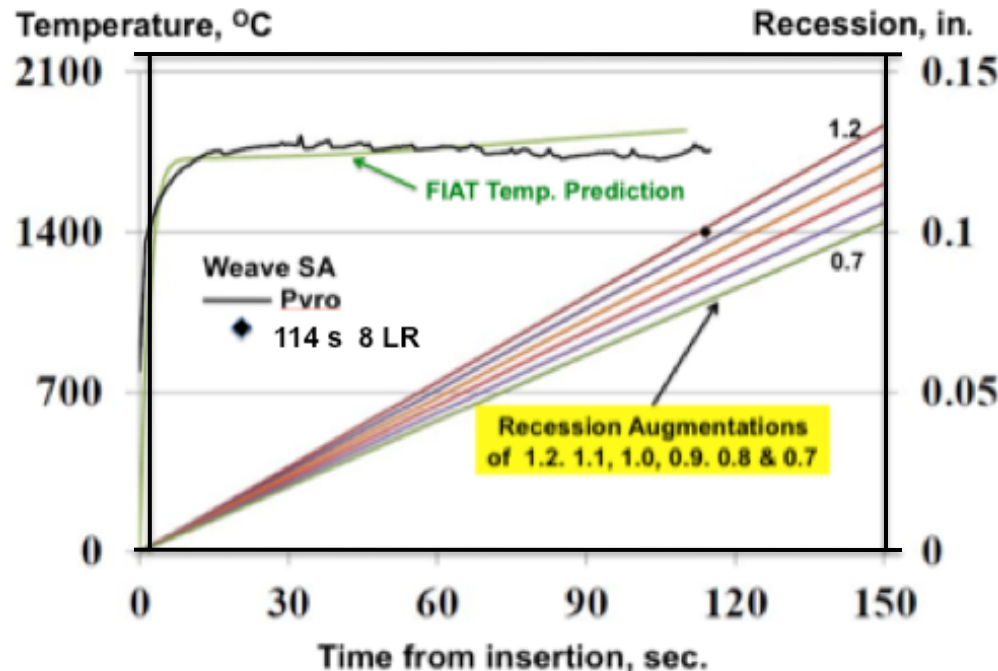
- Measured time for TPS 4 Layer Removal (4 LR) is similar for weaves SA and D (78 vs 75 seconds).
- FIAT with Recession Augmentation (RA) of 0.9 to 1.0 on an equivalent 0.1" solid layer matches the measured 4 LR times (~ 2 X that for 0.05" recession of equivalent solid carbon).
- Pyrometer temperatures compares well with the FIAT prediction assuming fabric emissivity is 0.9. IR camera temperatures are slightly "high" owing to a known scattered light issue.
- Based on these results and VITaL's heat load, base line Weave SA "TPS" thickness was doubled, such that it has 8 sacrificial TPS layers and 4 structural layers for a total of 12 layers.

Weave SA at 246 W/cm² and 9.6 kPa and Comparison to FIAT Predictions



- Shorter 4 LR time of 44.4 seconds “reasonable” owing to higher heat rate.
- FIAT predicted recession with *RA* of 0.7 on 0.1” solid layer matches 4 LR time. (4 LR ~ 2 X recession on equivalent solid carbon). Similar to results at lower heat rate.
- Pyrometer data saturated. IR camera data ~ 100 °C high due to known scattered light issue. FIAT temp. prediction “agrees” with measurement from IR camera.

BLAM Test at 136 W/cm² and 9.1 kPa 12 Layer Fabric in Ames IHF Under Bi-Axial Loading²



- Longer TPS layer removal time (same heat rate, but 8 TPS layers vs 4 for the JSC Tests).
- FIAT predicted recession with *RA* of 1.2 on 0.15" solid layer matches 8 LR time. (8 LR ~ 2 X recession on equivalent solid carbon). Similar to result at same heat rate from tests in JSC facility, on a 0.1" fabric and ~ 3 X higher pressure. Suggests diffusion controlled oxidation is the dominant thermophysics.
- Excellent agreement between FIAT and the pyrometer temperature measurement.

² Peterson, K. H., et. al., *Thermal and Structural Performance of Woven Carbon Cloth For Adaptive Deployable Entry and Placement Technology*, AIAA Aerodynamic Decelerator Conference, Dayton Beach FL March 25-28 2013

B'



- **B' is the ratio of the outgoing mass flux from the ablator surface to mass flux of the incoming free stream.**